Improving EUV imaging at tighter pitch using a tuned-multilayer mask stack

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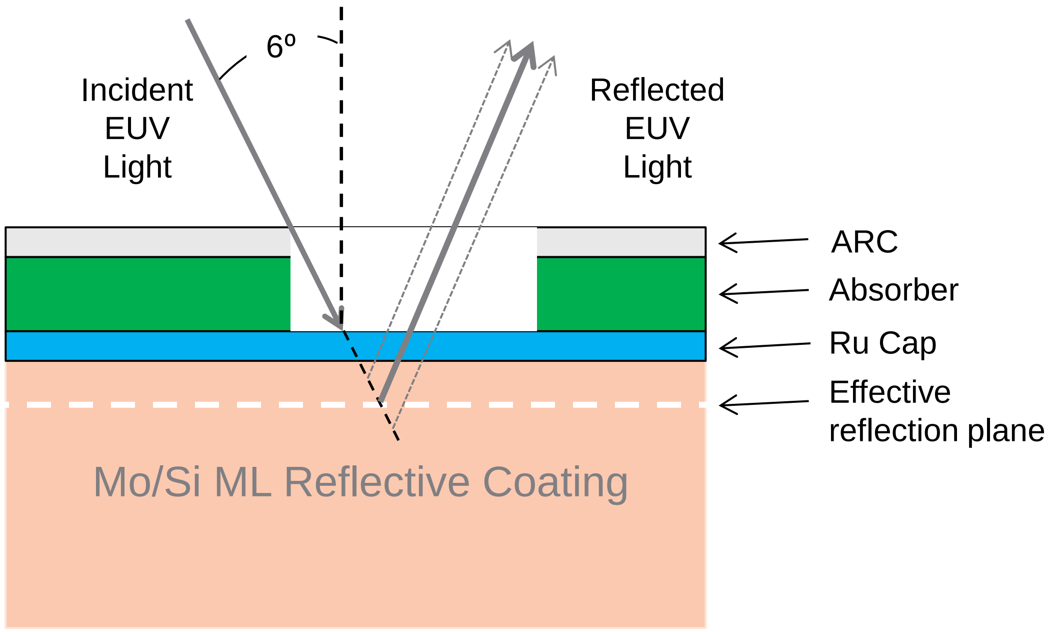
Outline of Presentation

- Introduction
- Review of 3D mask effects
- Compensation of telecentricity errors by multilayer (ML) tuning
- Summary of experimental data
- Possible next steps
- Conclusions

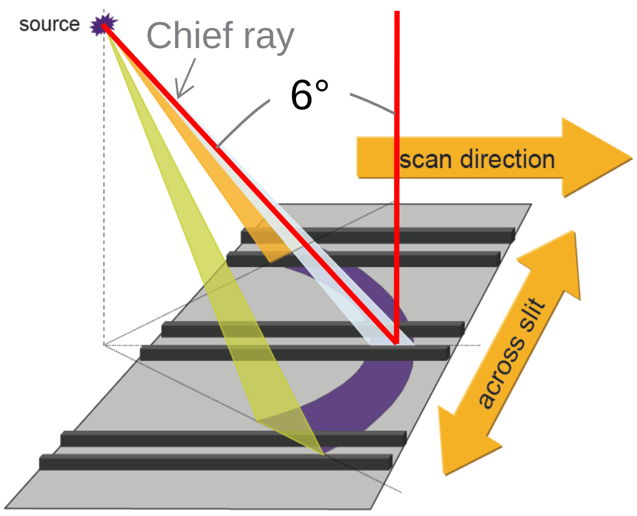
1. S. Raghunathan, et al., "Characterization of telecentricity errors in high-numerical-aperture extreme-ultraviolet mask images," EIPBN 2014, Paper 9B-4.
2. V. Philipsen, et al., "Imaging impact of multilayer tuning in EUV masks: experimental validation," SPIE Photomask 2014, Paper 9235-8.

3D Mask Effects: Mask Shadowing

EUV Mask Architecture



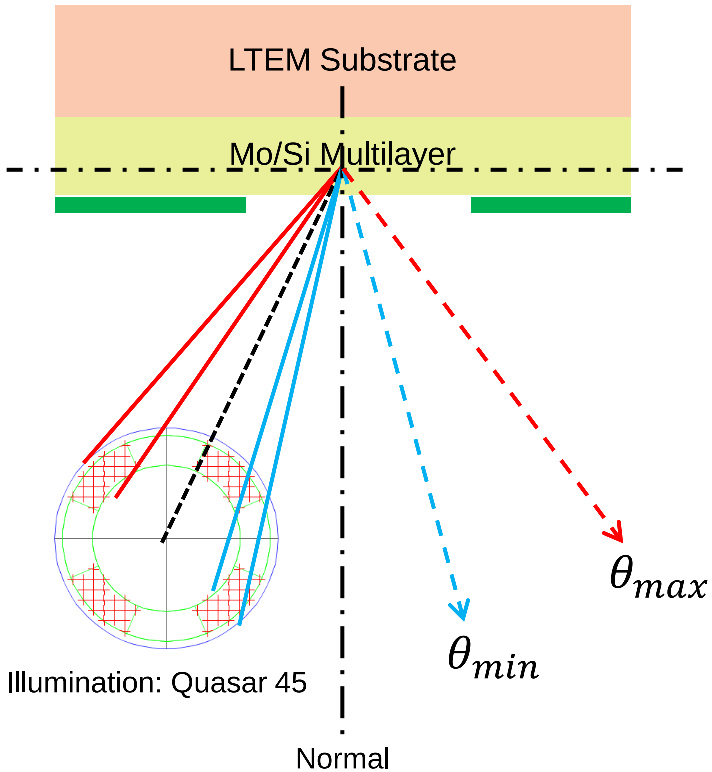
Mask Shadow Effect

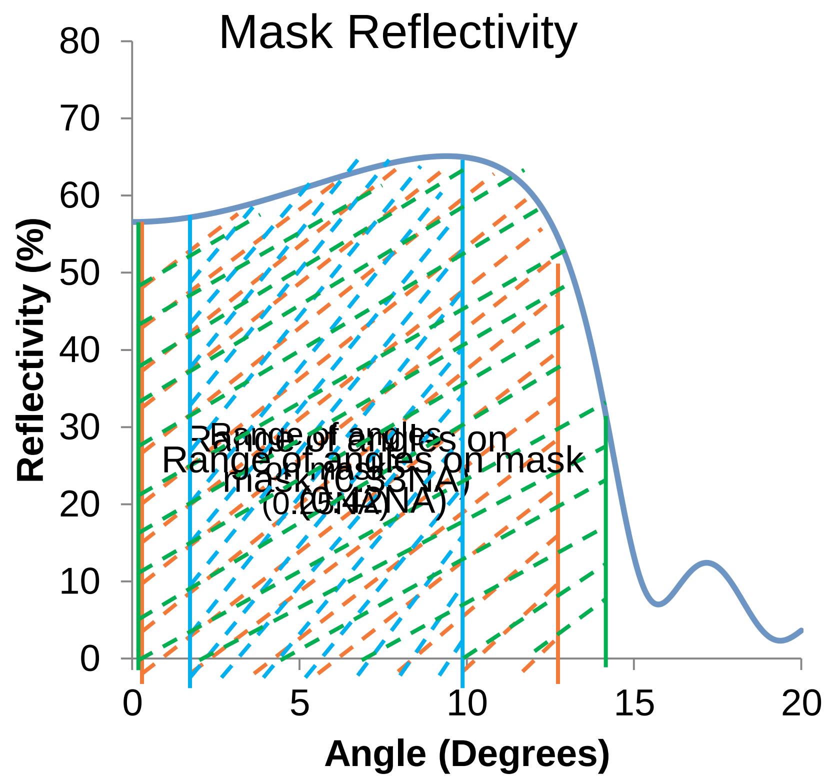


- EUV masks are Bragg reflectors; reflectivity depends on angle of incidence, ML period, & wavelength

- The shadow created by the mask absorber leads to a horizontal-vertical print difference (HVPD).
- HVPD can be partially compensated with a mask bias (HVB).

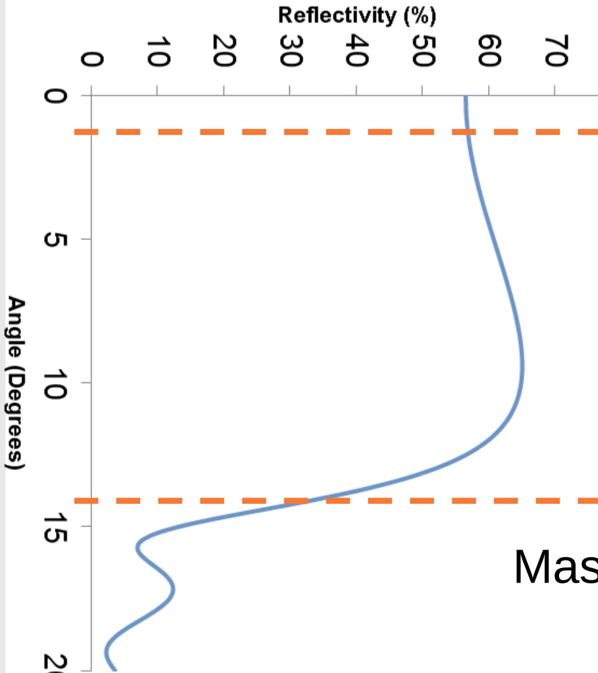
3D Mask Effects: Reflectivity Apodization

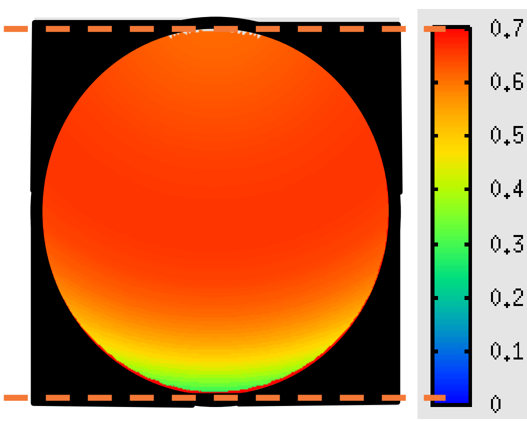




- Angular range on the mask increases with numerical aperture (NA)
- Higher NA leads to reflectivity apodization and larger telecentricity errors

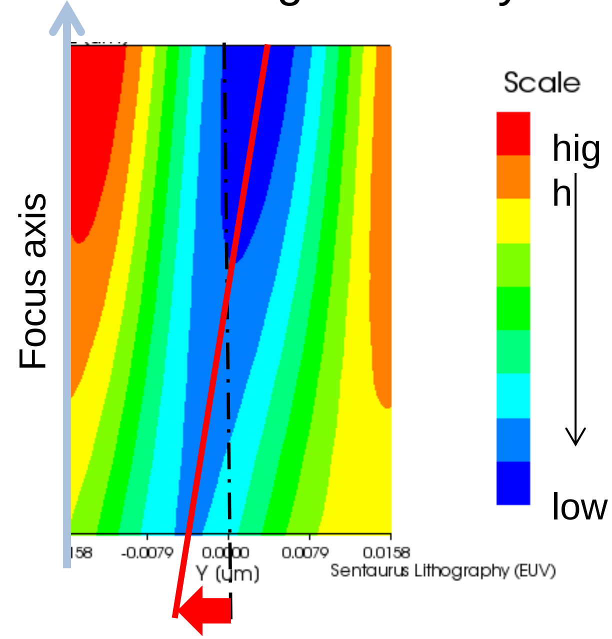
3D Mask Effects: Telecentricity Errors





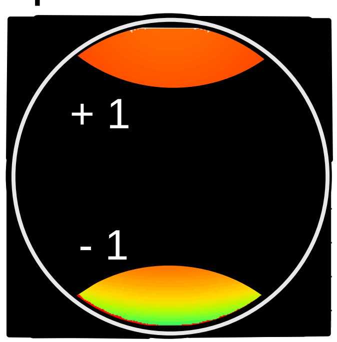
Mask Reflectivity across Pupil
(0.42 NA)

Aerial Image Intensity



Pattern shift through focus

Dipole Illumination



±1 order imbalance

Horizontal L/S

- Telecentricity error is defined as:

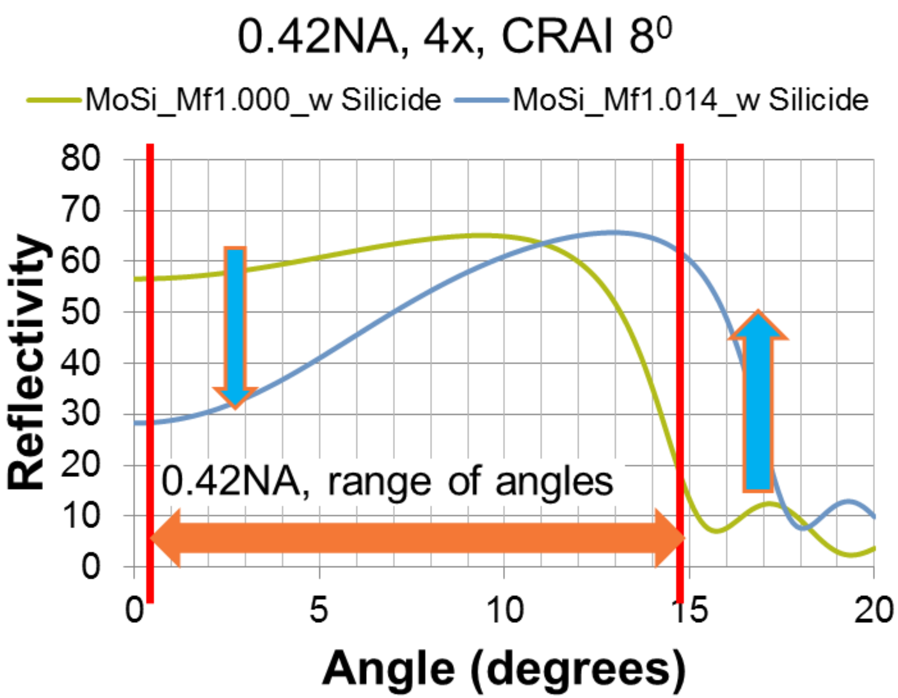
$$TE = \frac{Pattern\ Shift}{Focus\ Range}$$

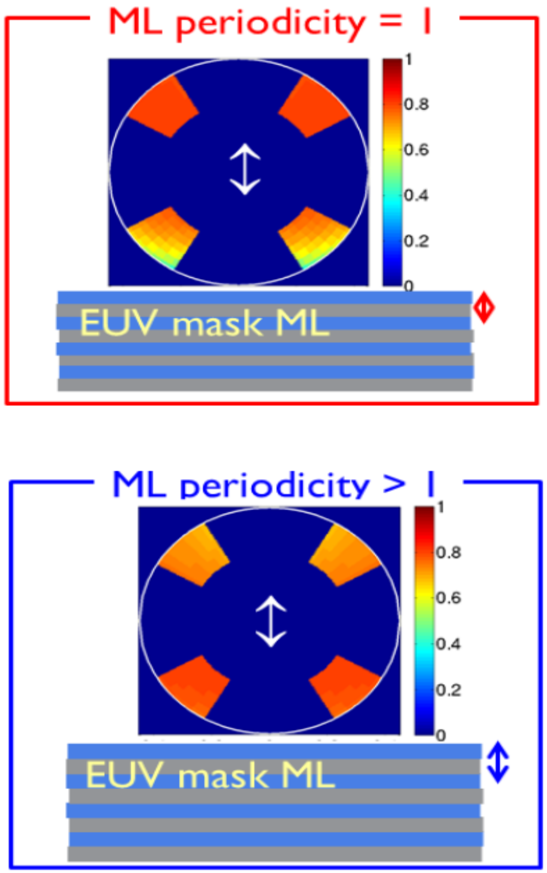
- For example,

$$TE = 20\ mrad = \frac{2\ nm\ Pattern\ Shift}{100\ nm\ Focus\ Range}$$

Compensation of Telecentricity Errors by ML Tuning

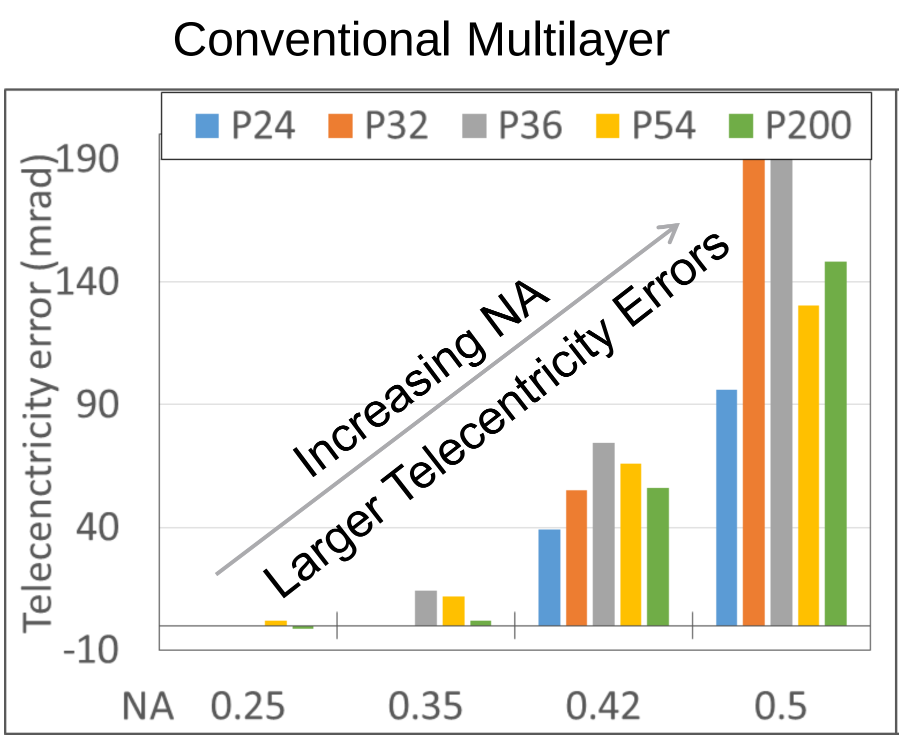
- Example of ML Tuning

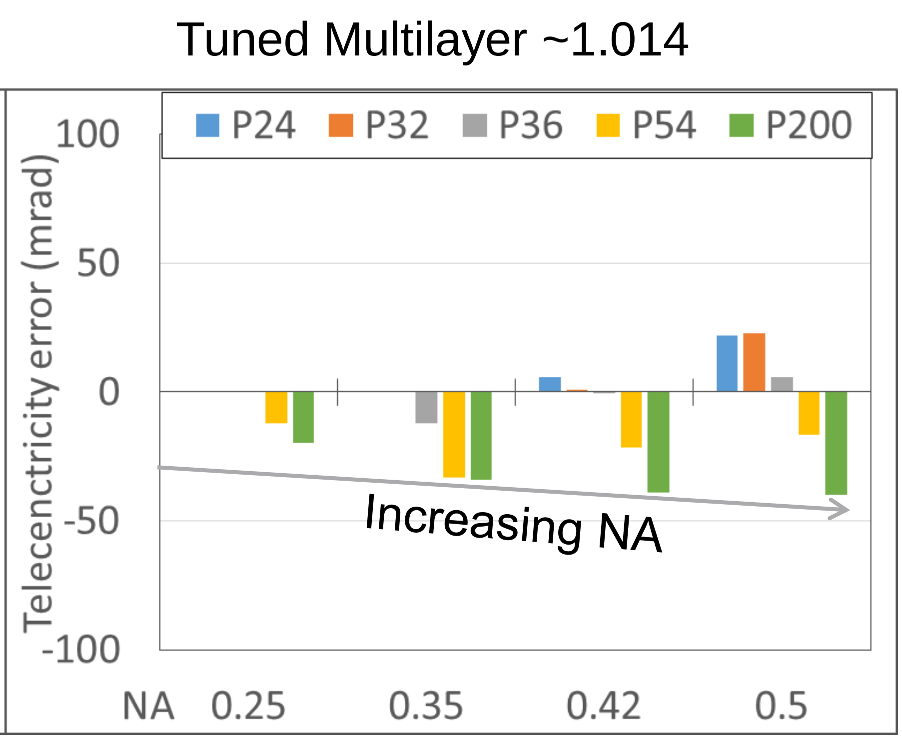




- ML tuning (modifying bilayer thickness) improves reflectivity at large incidence angles but decreases reflectivity at small incidence angles.
- ML tuning may be required for NA beyond 0.33.

Simulation of Telecentricity Error versus NA





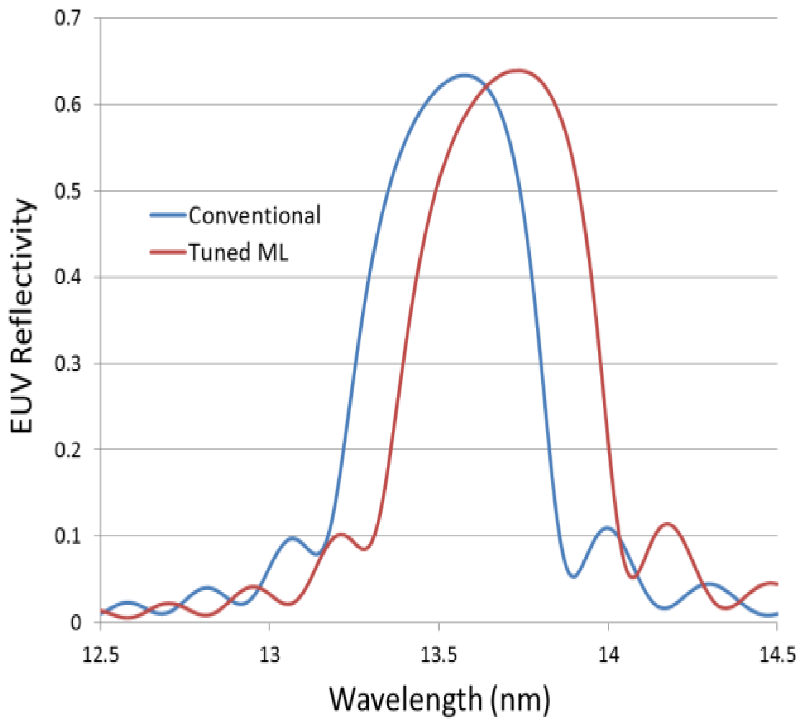
- Telecentricity errors will make a significant contribution to overlay budget at higher NA’s

- ML tuning can reduce the magnitude of the telecentricity errors at one specific pitch/illumination
- ML tuning is most effective when optimized at the tightest pitch

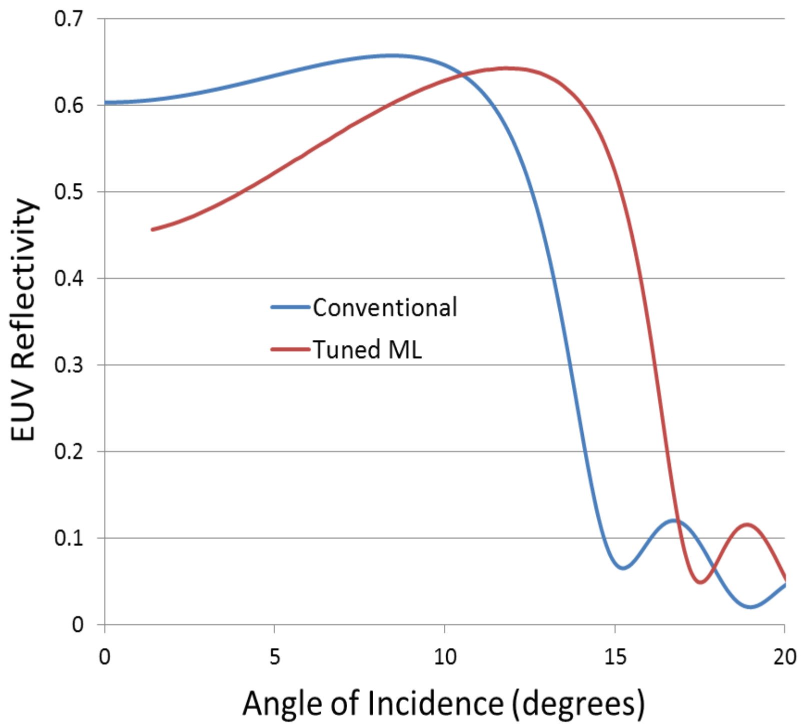
Experimental Data: EUV Reflectivity of Mo/Si MLs

- Measured reflectivity for masks with a conventional Mo/Si ML coating and with a tuned-ML coating with a ML-factor = 1.014

Reflectivity vs Wavelength



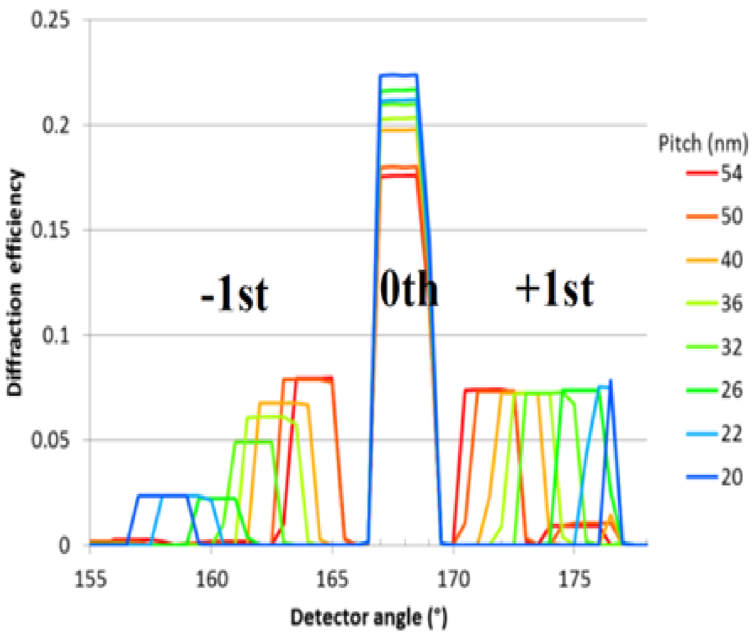
Reflectivity vs Incident Angle



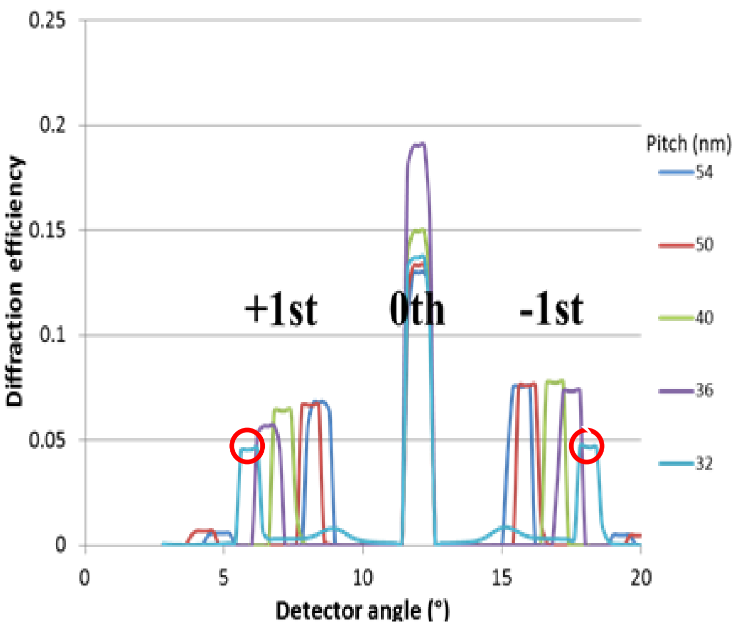
Experimental Data: Diffractometry of Tuned Mo/Si ML

- Measured diffraction spectra for horizontal 1:1 LS gratings at 6 degree angle of incidence and different pitches

Conventional Mo/Si ML



Tuned Mo/Si ML ~1.014)

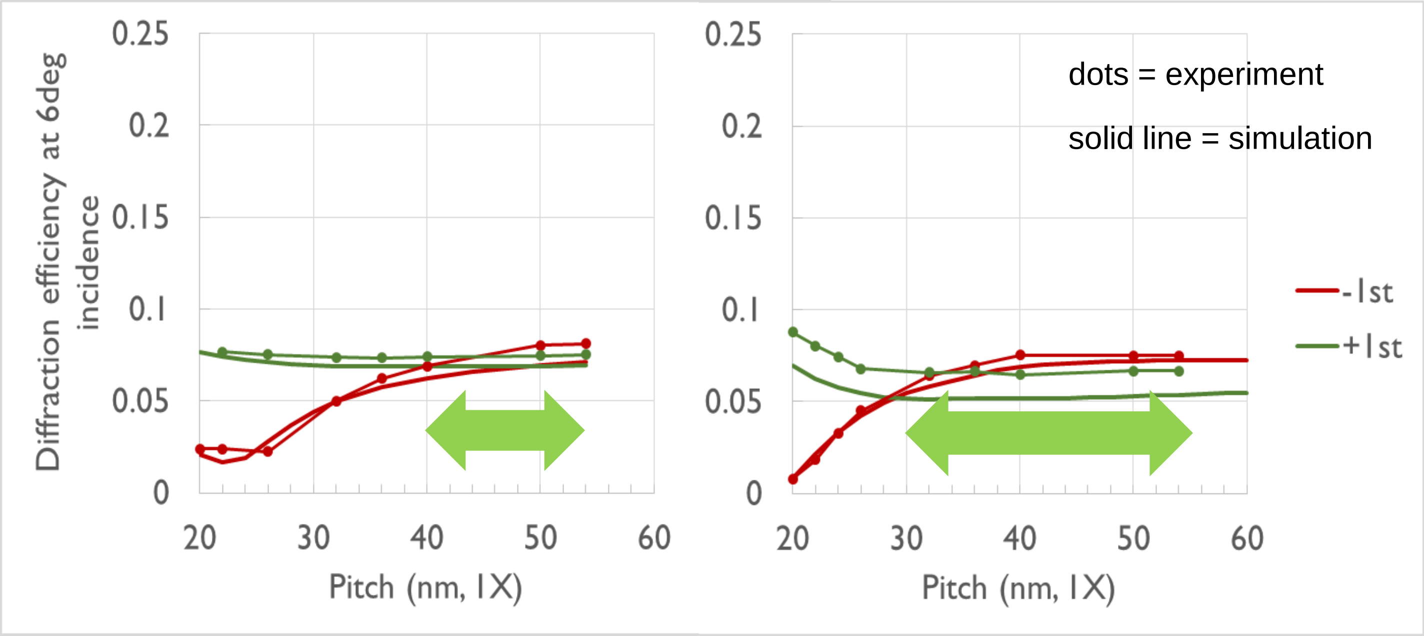


- The +1 and -1 diffracted orders are in better balance on the tuned-ML mask particularly at the tightest pitch

Comparison of Diffractometry Data with Simulation

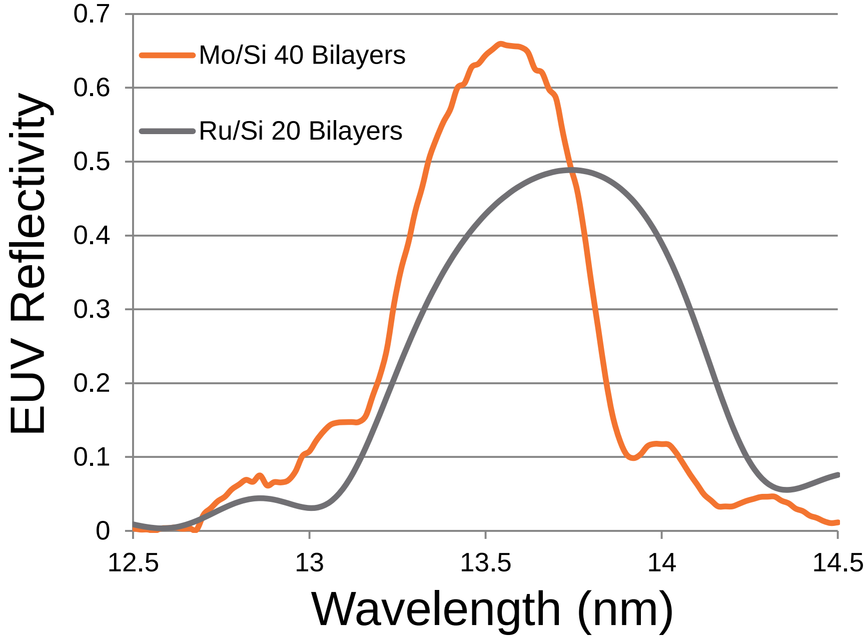
- Measured diffraction spectra for horizontal 1:1 LS gratings at 6 degree angle of incidence and different pitches

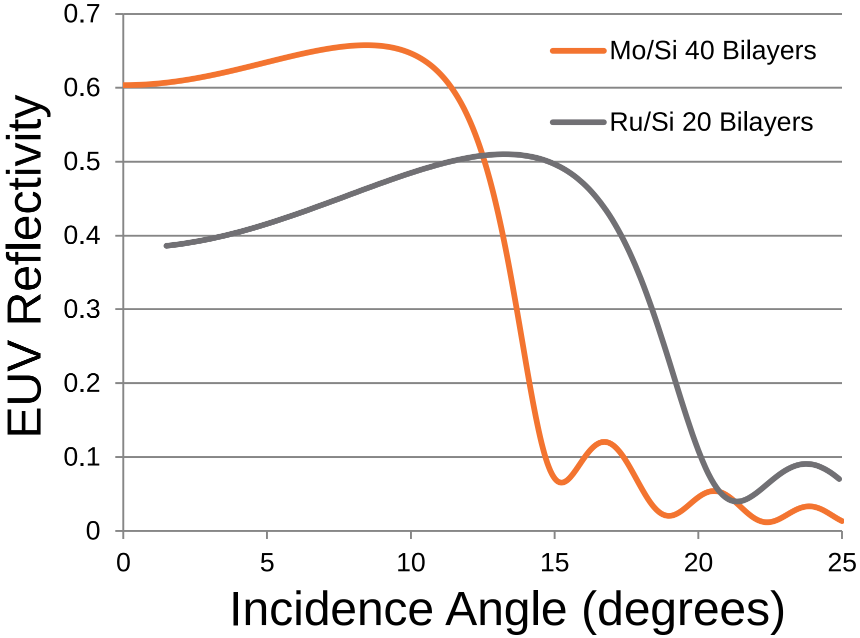
Conventional Mo/Si ML Tuned Mo/Si ML ~1.014



- Our calibrated mask model can predict behavior of +/-1st diffraction orders
- Multilayer tuning extends diffraction balance down to 30 nm pitch

Possible Next Steps: Alternative ML Materials

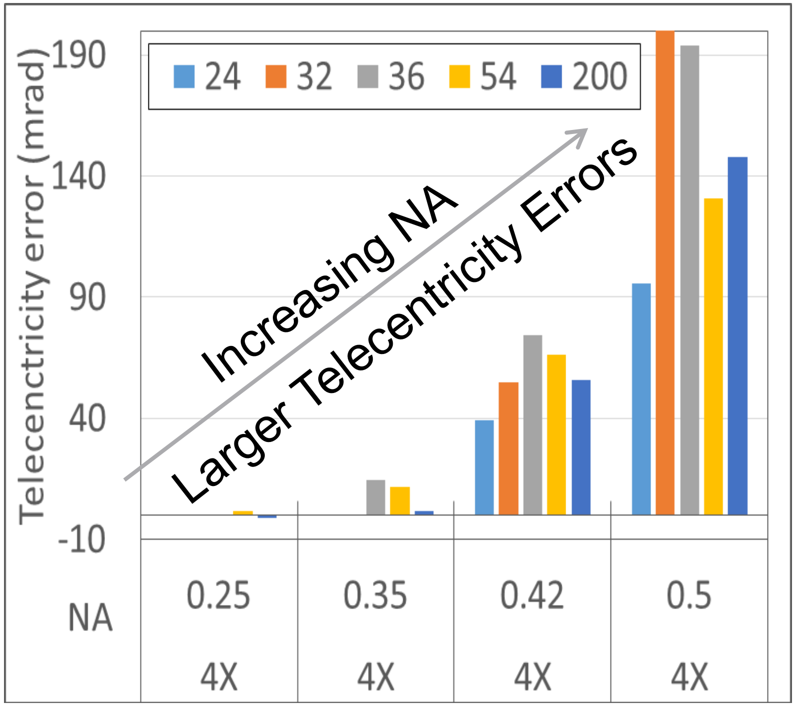




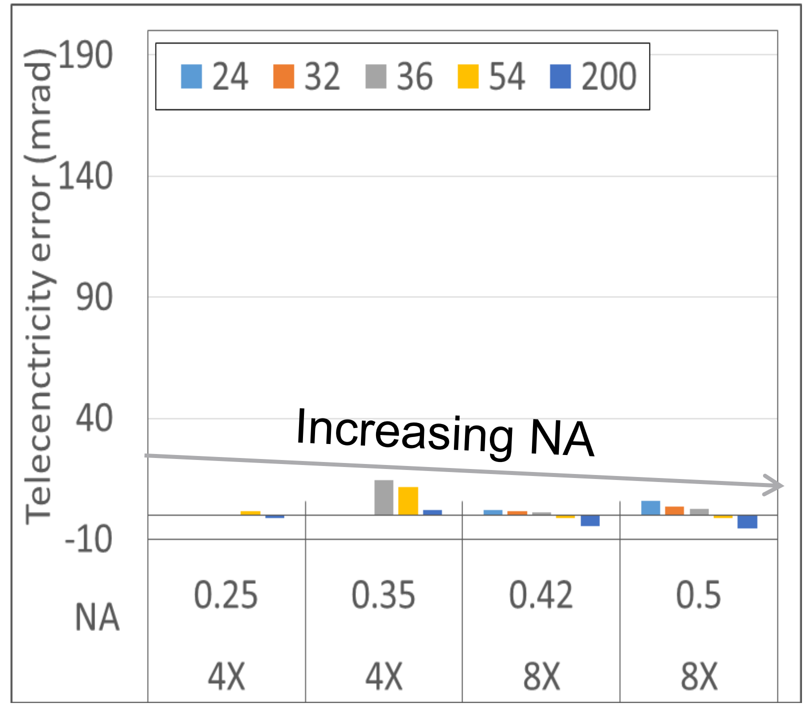
- Ru/Si ML coatings (even when unoptimized) have a much wider reflectance bandwidth than Mo/Si ML coatings
- The effective reflectance plane of Ru/Si ML coatings is ~100 nm closer to the coating surface
- Ru/Si ML coatings should result in a smaller mask shadow effect and smaller telecentricity errors.

Possible Next Steps: Larger Magnification Ratios

Conventional Multilayer (4x Mag)



Conventional Multilayer (High NA @ 8x)



- Larger magnification ratios reduce telecentricity errors and simplify mask manufacturing
- Larger magnification ratios are already being considered for next generation systems. See, for example, M. van den Brink, "Many ways to shrink: the right moves to 10 nm and beyond," SPIE Photomask 2014, Paper 9235-1

Conclusions

- 3D mask effects give rise to horizontal/vertical print differences, through-pitch best focus shifts, and through-focus pattern placement errors.
- At 0.33 NA, the conventional Mo/Si ML mask stack is applicable over a wide range of pitches.
- At higher NA values, the angular range on the mask increases leading to greater absorber shadowing, larger reflectivity apodization, and a diffraction imbalance in the pupil, particularly at tighter pitches.
- The ML period can be tuned to compensate for the diffraction imbalance at tight pitches over a limited range, but cannot effectively compensate for the diffraction imbalance at looser pitches.
- A tuned Mo/Si ML has little or no effect on absorber shadowing, but an advanced stack with a different choice of ML materials or an increase in mask magnification ratio should be able to simultaneously reduce telecentricity errors and mask shadowing.

Acknowledgements

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